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EVALUATION OF ELECTROMAGNETIC MEASUREMENTS WITH REGARD TO HUMAN EXPOSURE STANDARDS

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13. ABSTRACT *(Maximum 200 words)*
The effects of radio frequency (RF) and extremely low frequency (ELF) electromagnetic fields can produce biological effects that can be harmful to human health. Both thermal and field effects are possible. This report estimates the effects of human exposure to electromagnetic fields in four frequency regimes: 60 Hz. (high voltage power lines), 28 KHz. (Very low frequency (VLF) communication systems extendible to 10-30 MHz range), and 900 MHz (cellular communication systems). An outline of the approach needed to analyze the 70-144 MHz communication range is given but no results were generated in this effort. The known thermal and non-thermal effects are reviewed. Hazardous exposure situations are investigated including epidemiological studies, laboratory exposure to animals and in vitro studies at the cellular level. Guidelines are suggested for the ELF, VLF and cellular telephone frequencies. The scaling of measurements is discussed along with approximate analytical results. Health standards are presented, and conclusions and recommendations are given. The report also includes an extensive bibliography. Appendix A has an evaluation of government furnished field measurements with regard to IEEE and ANSI standards. Appendix B contains one preprint and three preprints of papers supported by or related to this work.

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Table of Contents

List of Tables

Executive Summary

Radio frequency (RF) and extremely low frequency (ELF) fields can produce biological effects that can be harmful to human health. Both thermal and field effects are possible. Heating does not play any significant role in the case of field effects. A review of EM radiation standards was carried out and the effects of EM fields on humans as reported in the extensive literature on the subject were studied. Emphasis was placed on separating studies on thermal effects from those on non-thermal effects.

Analytical work on determining EM fields in the body has been accomplished for three specific cases: 60 Hz, 28 kHz, and 900 MHz. The 60-Hz study is concerned with finding the currents induced in the body of a human standing under or near a high-voltage power line. The 28-kHz study is related to the Navy submarine communication system located near Annapolis, MD. Finally, the 900-MHz work is related to determining the fields induced in the human head due to a closely coupled cellular telephone. The intermediate communication band extending from 70–144 MHz was not included in the present study. An outline of a solution for this frequency range is discussed. Detailed results and analysis for the frequency ranges covered are presented in the form of published or submitted technical papers.

At low frequencies, the question of electric and magnetic field effects as separate entities was investigated. Here results show that there is a big contribution due to the larger induced fields and currents tangential to the body. Using an exposure situation, due to high-power lines, epidemiological results on children were evaluated. However, epidemiological studies do not provide satisfactory exposure situations to be useful in locating credible data associated with cellular non-thermal effects of exposure to electromagnetic fields. *In vivo* studies of exposure of laboratory animals to electromagnetic fields were evaluated for effects. Since experiments with living animals neglected the large *electric* field in the body, a scaling problem occurs, which affects exposure situations for safety guidelines. *In vitro* studies at the cellular level led to EM field levels which produced meaningful effects. Frequency ranges here were 60 Hz and 30–300 Hz. *In vitro* studies of the effect of exposure to EM fields in the VLF range of frequencies do not appear to have been carried out in any extensive

manner. *In vitro* studies by others at frequencies in the range 0.1–100 Hz are extensive and clearly indicate significant cellular effects from exposure to EM fields. Exposure situations and suggested guidelines are also given for different ranges of frequencies.

A discussion of EM radiation standards is given along with suggestions for setting up more meaningful standards than those existing presently.

An evaluation of government-furnished field measurements was carried out using IEEE and ANSI standards. It should be noted that no general conclusions can be drawn from the measurements. Conclusions are only relevant to the specific antenna systems and environment described in this report.

This report contains an extensive bibliography with important papers noted. A conclusion and recommendation section is included. One important conclusion is that meaningful EM exposure standards are not presently available.

1. Introduction

Concern has been expressed by workers, as well as the general population, that radio frequency (RF) and extremely low frequency (ELF) fields can produce biological effects that can be harmful to human health. The RF and ELF fields produce a variety of thermal effects, depending on whether the exposure levels are high or low. In addition, field effects are possible in which heating does not play any significant role (i.e., non-thermal effects). National and international agencies have published guidelines and standards on human exposure limits. The basis for their work rests on established data appearing in the literature.

It is instructive to look at the EM exposure problem with a view towards its hierarchical structure. On the global level, the whole body may be exposed to excessive levels of non-ionizing radiation, which affects cells everywhere. The body's response is to destroy the affected cells, and in doing so it causes great damage or even death. There have been cases in the past where unsuspecting people have unknowingly been exposed, feel warmth, and later experience grave consequences. At another level of exposure, distant or near sources, such as power lines or cellular telephones, affect certain parts of the body, such as the bone marrow or the brain. Here it is found that some organs are more sensitive than others to both thermal and non-thermal EM exposures. At still another level, very small fields can affect biological processes in the body. One example is the influence of induced fields on nerve transmission by a change in the ion movements in the nerve fibers. Looking at the problem as a whole, it is seen that there are many ways in which the body responds to EM exposure, and general approaches will not be fruitful. The mandate then is to investigate specific exposure situations and try to correlate known local field values in the body with their biological effects.

This program involves a number of interrelated problems. One problem has to do with the basis for EM standards, namely fields and power densities external to the body. Essentially, this involves far-field concepts independent of the distance to the source. In reality, sources which are electrically near the body produce different fields inside the body than those produced by plane (i.e., far-field) waves. This differentiation of close and distant sources can

be loosely called near- and far-field cases. Original standards were based on heating effects due to distant sources which produced plane-wave fields in the vicinity of a human body. Near-field cases are more difficult to evaluate, not only because the fields are more complex, but also because one must know the details of the radiating system and the specific part of the body being exposed. Thus there is a specificity attribute of the near-field problem that does not occur with distant sources. Another problem concerns fields maintained by pulsed sources where the average power is small but the maximum field is large. Consequently, biological effects are possible due to high instantaneous fields. These effects have to be differentiated from CW fields which are involved with tissue heating. As a last consideration, it will be necessary to investigate the specific physical arrangements where the measurements were taken in order to come to any conclusions. It can be said that EM radiation exposure studies cannot be done in general, since they require specific physical and EM information.

2. Results for Different Frequency Regimes

2.1. 60-Hz Power Frequency

The electromagnetic field at all points near a high-voltage transmission line was determined in analytical form. Account was taken of the presence of the earth below the three-wire, three-phase power line. The electric and magnetic fields, the total axial current, and the current and power densities in the interior of a human body were determined when the body is under or near the line, or reclining in a bed near the height of the line. The fields are very weak, and the current and power densities so small that thermal effects can be ignored, but not necessarily possible effects on nerve action, the functioning of cells, or on certain secretions.

The work summarized above is found in Appendix B in a paper by King and Wu entitled "The complete electromagnetic field of a three-phase transmission line over the earth and its interaction with the human body" [1].

Additional work on the 60-Hz case, which is extendible to the 10–30 MHz range, was done by King and Sandler and is to be found in Appendix B. It appears in the paper titled

"Electric fields and currents induced in organs of human body when exposed to ELF and VLF electromagnetic fields" [2]. In this research, the fraction of the total axial current, the axial current density and the axial electric field in each organ of the body were obtained at any desired cross section. The electric field here is the average macroscopic field in which cells in each organ are immersed, when the whole body is exposed to a known incident field. It corresponds *in vivo* to the electric field used *in vitro* to expose cells in tissue.

2.2. 28-kHz Case Extendible to the 10–30 MHz Range

The VLF transmitter located on a peninsula near Annapolis, MD, maintains strong electric and magnetic fields in the adjacent urban areas. These were determined at selected locations and then used to evaluate the currents and associated electric field induced in the human body. The work summarized above will be found in Appendix B in a paper entitled "Electromagnetic field in human body due to VLF transmitter," by King and Harrison [3].

2.3. 900-MHz Cellular Telephone Operating Near the Head

The accurate determination of the complete electromagnetic field penetrating through the skull into the brain, due to a cellular transceiver was determined. The specific absorption rate (SAR) was also determined. The results of this work are given in Appendix B in a paper by King entitled "Electromagnetic field generated in model of human head by simplified telephone transceiver" [4].

2.4. Outline of Approach to 70–144-MHz Communications Frequencies

The intermediate communication band extending from 70–144 MHz was not included in the present study. This is because the body is of the order of a wavelength, and the theory requires a special formulation which is different from the other cases covered in this report. The basic electromagnetic model is a solid lossy dipole immersed in an incident field. Although there is not sufficient time to attack the problem, it could be done in a future

study.

Analysis relative to linear antennas in free space is found in the book by King entitled *The Theory of Linear Antennas* [5]. For a human with length 1.75 meters, corresponding dipole lengths would be in the range from 0.42λ to 1.22λ. This assumes the dipole is perfectly conducting, and one is concerned only with the field outside the dipole, not inside. The electrical properties of the body are

$$\sigma = 0.5 \text{ S/m} \qquad \text{(conductivity)}$$

and

$$\epsilon_r = 40, \qquad \text{(relative dielectric constant).}$$

Note that the dielectric constant ϵ is $\epsilon = \epsilon_0 \epsilon_r$, where $\epsilon_0 = 0.8854 \times 10^{-11}$ F/m. The skin depth d_s is the distance in which a wave decreases to e^{-1} of its original value, and is given by

$$d_s = \sqrt{2/\omega\mu\sigma},$$

where

$$\omega = 2\pi f,$$

$$\mu = \text{magnetic constant},$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ henry/m} \qquad \text{(free space).}$$

At 70 MHz and 144 MHz, the skin depths are 8.5 cm and 6.9 cm, and the human body cannot be considered perfectly conducting.

This result is quite different from the 60-Hz case, where the skin depth is large compared to the diameter of the body. Much work has been done on bare and insulated antennas in sea water by King and Smith as reported in the book *Antennas in Matter* [6]. However, the human body does not act electrically as a perfectly conducting bare or insulated antenna in the frequency regime under consideration. Furthermore, because of the relatively high value of the dielectric constant, the transverse dimensions are not electrically small due to the $\sqrt{\epsilon_r}$ increase in wavelength in the body.

An outline of the solution is as follows. A relevant integral equation or equations would be found that satisfy the boundary conditions on the surface of the equivalent dipole. Using an incident electric field, interior currents in the dipole would be found. Approximate general solutions for the currents would be checked in specific cases with numerical procedures, such as the FDTD (Finite-Difference Time-Domain) method. Simple functional expressions for the interior currents would be useful not only for determining the electric field in the body, but also for physically understanding the system and its dependence on basic parameters such as frequency and body size. The resonance curve would not be sharp, as in the case of a perfectly conducting dipole. It would also depend on the transverse dimensions. As in the ELF case carried out under the present study, the electric field, total current and current densities could be calculated for the various organs in the body. It should also be noted that work on the 70–144 MHz range can be extended to 400 MHz.

3. Known Credible Thermal and Non-Thermal Effects

3.1. Credible Data Relative to Non-Thermal Effects of Exposure of the Human Body to Electromagnetic Fields

The investigation of possibly deleterious effects of exposure to electromagnetic fields is a complicated problem. To begin with, it involves the identification of such effects in a great variety of exposure situations over wide ranges of frequency, intensity, and duration. This study will emphasize practically meaningful and theoretically useful situations in a *low-frequency* range that extends from 50 Hz to 30 MHz throughout which the human body is electrically short and a *high-frequency* range from 0.9 to 1.8 GHz. This includes the fields of 50- and 60-Hz power lines, 10- to 30-kHz VLF shore-based transmitters, 10-kHz to 30-MHz shipboard transmitters, and the fields of cellular telephones. The intermediate range from 30 to 150 MHz, which includes full-body resonance, is omitted from this report since it requires a different analytical approach.

3.1.1. Thermal and Non-Thermal Effects

Observed effects of electromagnetic fields have been separated into *thermal* and *non-thermal* groups. Thermal effects involve increases in temperature due to exposure to an electromagnetic field. The incident field induces electric currents in the body as a whole or localized in a particular part or organ. Since the electron and ion conductivity σ_0 is finite and the relative permittivity $\epsilon_r = \epsilon' + i\epsilon''$ is complex, electric energy is converted into heat. This can be helpful as in the hyperthermia treatment of tumors, deleterious as in its effect on the eye, or harmless as in the clicks in the ear. Note that these are all macroscopic effects that involve the macroscopic permittivity and conductivity. Microscopic non-thermal effects involve the cells and molecules in the tissues of a particular organ. The electric and magnetic fields induced in the different organs or parts of the body are macroscopic average quantities that interact with charges on cells and molecules to generate local fields particularly at the cell membranes. It is much more difficult to identify non-thermal effects than thermal ones.

3.1.2. Electric and Magnetic Fields

The electromagnetic field consists of two vector quantities, the electric and the magnetic fields. These are interrelated in a complicated manner in Maxwell's equations that involves electric charges and currents. The latter may be conduction currents, polarization currents, or magnetization currents. In the absence of magnetic materials, the last named are nonexistent. The electric and magnetic fields are independent only when they are time-invariant as in electrostatics and direct currents. All thermal effects in the human body involve only the electric field in the quantity $\sigma_e E^2$, where σ_e is the real effective conductivity $\sigma_e = \sigma_0 + \omega\epsilon''$. Important cellular effects have been shown experimentally [7] to involve only the electric field when exposed to either an electric or a magnetic field. The latter induces circulating electric currents and electric fields in the tissues and across cell membranes. Clearly, standards for exposure must involve the magnitude and direction of the electric field induced in the organs of the body.

Unfortunately, conventional wisdom has promoted the idea that at low frequencies primarily exposure to magnetic fields is harmful. This belief seems to be based on the erroneous

assumption that the boundary condition on the normal component of the electric field on the surface of the body is sufficient to determine the electric field and current in that body. The correct formulation is based on the boundary condition for the tangential component of the electric field. It leads to the well-known integral equation for the axial current. This can be solved in simple form for the human body at frequencies for which this is electrically short. From the total axial current, the axial components of the electric field and of the current density are readily evaluated. These are much greater than the small radial currents that charge the surface and also larger than the circulating current and electric field associated with the simultaneous exposure to the transverse magnetic field.

It seems evident that a meaningful exposure metric can be established in terms of the electric field induced in the body since this is known to be involved in eliciting cellular effects. This means the externally applied electric field is the dominant factor and its magnitude and direction should be involved in the exposure metric. With reference to power-line fields, the large vertical electric field E_z^{inc} is directly related to the large transverse magnetic field B_y^{inc} by the simple formula $E_z^{\text{inc}} = cB_y^{\text{inc}}$ when the current and voltage are traveling waves. However, this is an ideal condition that is well approximated only with high-voltage lines that transmit megawatts of power to a single distant load in the form of a transformer station. The field of other types of power lines with distributed loads are difficult to determine analytically. Accordingly, useful exposure situations are best sought with reference to high-voltage lines with a predominantly traveling wave of current and voltage.

At VLF and higher frequencies, the incident fields are generated by vertical antennas on the surface of the earth. Depending on the distance from the source, the near field as well as the far field may be involved.

3.2. Identification of Hazardous Exposure Situations

The problem at hand is the identification of non-thermal effects of exposure to electromagnetic fields in well characterized exposure situations. There are several approaches to relating, for example, the incidence of cancer to exposure to electromagnetic fields. The following are important.

3.2.1. Epidemiological Studies

The difficulties in obtaining meaningful statistical data and the even greater problems in interpreting the data obtained are discussed in detail by Carstensen [8], specifically with reference to exposure to 50–60-Hz magnetic fields and the incidence of cancer. In reviewing more than 100 epidemiological studies and attempting to evaluate them quantitatively, he concludes that "the presumably exposed population has essentially the same health characteristics as the population as a whole." However, simply averaging all available data may not yield the right answer since the reliability of different epidemiological studies is far from equal. The most recent investigation by Feychting and Ahlbom [9] confirms earlier work that indicates a 2.5 to 3 times greater likelihood of leukemia among children that have grown up near high-voltage power lines as compared to those living far away. And in this study special care has been taken to assure as great a reliability as can probably be achieved.

Exposure is measured in terms of time averages and Carstensen estimates this to be "low" when the magnetic field in which the person is immersed is $0.1\ \mu\mathrm{T} = 1$ mG and "high" when it is $0.4\ \mu\mathrm{T} = 4$ mG. The data of Feychting and Ahlbom [9] included everyone under 16 who had lived on a property within 300 m of any of the 220- and 400-kV power lines that extend for 15,000 km over Sweden. This group was exposed to calculated magnetic fields that took full account of "the height of the towers, distance between towers, distance between phases, the ordering of phases, and the load on the line." These can be compared with calculations in King and Wu [1], where formulas, tables, and graphs are given for all of the components of the electric and magnetic fields of a 100-kV three-phase, three-wire power line carrying 300 A. The vertical component of the electric field and transverse component of the magnetic field at a height $z = 2$ m above the ground and at the distance y measured from directly below the central wire are shown in Table 1.

If the voltage of the power line is doubled and quadrupled to correspond to lines in the Feychting and Ahlbom [9] study, $|E_z|$ and $|B_y|$ in Table 1 must be doubled (quadrupled) to give the values shown in Table 2.

Table 1. Electric and Magnetic Fields at Distance y and Height z above the Earth Near a Three-Wire, Three-Phase 100-kV Power Line

y, m	10	20	30	40	50	100	200	300
$\lvert E_z \rvert$, V/m	535	287	140	70	15.4	5.4	0.7	0.206
$\lvert B_y \rvert$, μT	1.78	0.96	0.47	0.23	0.051	0.018	0.0023	0.00069

Table 2. Like Table 1 but for 200-kV (400-kV) Power Lines

y, m	10	20	30	40
$\lvert E_z \rvert$, V/m	1070	574	280	140
	(2140)	(1148)	(560)	(280)
$\lvert B_y \rvert$, μT	3.56	1.92	0.94	0.46
	(7.12)	(3.84)	(1.88)	(0.92)

y, m	50	100	200	300
$\lvert E_z \rvert$, V/m	30.8	10.8	1.4	0.412
	(61.6)	(21.6)	(2.8)	(0.824)
$\lvert B_y \rvert$, μT	0.102	0.036	0.0046	0.0014
	(0.204)	(0.072)	(0.0092)	(0.0028)

Results obtained by Feychting and Ahlbom [9] are summarized in Table 3. For comparison, the calculated results of King and Wu [1] can be arranged as in Table 4.

A comparison of the results in Tables 3 and 4 shows that the risk ratios for leukemia of 4.3, 3.5, and 2.9 fall in the distance range ≤ 50 m; the risk ratios equal to or less than 1.1 are in the distance range ≥ 100 m. This shows complete consistency and indicates a risk for those living closer than 50 m from a high-voltage power line, and no risk for those living further away than 100 m from such a line.

Table 3. Risk Ratio (Leukemia) near 220- and 400-kV Power Lines with Magnetic Field and Distance as Variables*

Magnetic field (μT)	≤ 0.09	$0.1 \leq 0.19$	> 0.2
Risk ratio	1	4.3	3.5
Distance from line (m)	≥ 101 m	51–100 m	≤ 50 m
Risk ratio	1	1.1	2.9

*Adapted from Tables 7 and 8 in Feychting and Ahlbom [9]

Table 4. Ranges of Magnetic and Electric Field near 200- and 400-kV Power Lines as Obtained from Table 2

Distance from line (m)	≥ 100 m	100–50 m	50–10 m
Range of magnetic field (μT)	0.0014–0.072	0.036–0.204	0.102–7.12
Range of electric field (V/m)	0.412–21.6	10.8–61.6	30.8–2140

Since the power lines in Sweden are described by Feychting and Ahlbom [9] as all quite similar and not subject to large fluctuations in load, their electromagnetic fields should be quite well approximated by the field of a reasonably well-matched line with traveling waves of current and voltage. In this case, the electric field can be obtained from the magnetic field from the simple relations $E_z = cB_y$, $E_y = -cB_z$. Since the electric field parallel to the length of a human body induces axial currents that are much larger than the circulating currents induced by the transverse magnetic field, it should be the preferred metric. This choice is virtually mandated by the fact that axial current densities and electric fields in the organs of the body are quite simply related to the external power-line electric field, whereas this is not true of the circulating current densities and electric fields.

In a study by Bren [10], the conclusion is reached that "until a rigorous exposure metric is developed, the results of epidemiological findings will be difficult to interpret." To the extent that the magnetic fields calculated by Feychting and Ahlbom [9] can be related to the

associated electric fields, such a metric can be established. This follows because the axial current induced in the exposed human body can be determined and from this the electric field that acts at the cellular level in the lymph nodes and spleen, where the white-blood corpuscles involved in lymphocitic leukemia are made.

Epidemiological studies comparing the strong VLF exposure of residents of Annapolis, MD and its surroundings with residents of cities far from such high-power transmitters are unavailable. The same appears to be true of exposure to the fields of hand-held radio transceivers.

With the possible exception of the work of Feychting and Ahlbom [9], available epidemiological studies do not appear to provide satisfactory exposure situations to be useful in locating credible data associated with cellular non-thermal effects of exposure to electromagnetic fields.

3.2.2. In Vivo Studies of Exposure of Laboratory Animals to Electromagnetic Fields

The study of the effect of electromagnetic fields on living laboratory animals has many advantages over the corresponding studies on human beings. Notably, the individual specimens can be chosen for uniformity and the electromagnetic environment can be selected, maintained, and varied accurately and at will, so that the exposure situations are precise. However, to carry out identical exposure on a sufficient number of specimens and simultaneously maintain an equal number of controls is difficult and costly and has not been carried out. Carstensen's review [8] of the possible carcinogenic effect of exposure to magnetic fields indicates as many negative or inconclusive results as positive ones. Magnetic fields ranging from 0.1 μT to 0.1 T were used with no evident increase in positive results with increasing field strength. However, the postulate that stronger field exposure must exhibit greater effects is not necessarily applicable to nonlinear phenomena like those at the cellular level. Furthermore, exposure to magnetic fields induces only circulating electric fields and currents which are zero in a plane across the center of the body and increase linearly outward. As

shown in King and Wu [1], this maximum at the surface of the body is given by

$$\sigma_1 E_{1\theta}(\pm a_1, y', z) = J_{1\theta}(\pm a_1, y', z) = \frac{i\omega a_1 \sigma_1}{2} B_{0y}^{\text{inc}}(0, y', z),$$

where σ_1 is the conductivity of the body and a_1 is its mean radius at the particular cross section defined by z. Since the cross section of a mouse is approximately 2 cm in diameter and that of a man 30 cm, the induced current density and electric field in a mouse are 1/15 those in a man. In order to induce the same electric field and current density, the applied magnetic field must be 15 times that applied to a man. Since the magnetic field of a 200–400-kV traveling-wave power line at a distance of 10 m is $B_y^{\text{inc}} = 3.56\ \mu$T, the field applied to the mouse should be 53.4 μT.

Exposure to axial electric fields requires no scaling when the ratio of length to mean cross-sectional radius of an animal and a man are approximately equal. The formula for the axial current density in a body parallel to the incident electric field E_s^{inc} is

$$J_s(s) = \frac{I_s(0)}{\pi a_1^2}\left(1 - \frac{s^2}{h^2}\right),$$

where

$$I_s(0) = \frac{2\pi}{\zeta_0 \Psi} k_0 h^2 E_s^{\text{inc}}.$$

Here, a_1 is the mean radius and h is the half-length of the body. The parameter Ψ depends only on the ratio h/a_1. If the ratio h/a_1 is the same for a man and an animal, it follows with

$$J_s(s) = \frac{2\pi}{\zeta_0 \Psi} \frac{h^2}{\pi a^2} \frac{2\pi f}{c} E_s^{\text{inc}} \quad \text{and} \quad E_s(s) = \frac{J_s(s)}{\sigma_1},$$

that

$$\frac{[J_s(s)]_H}{[J_s(s)]_A} = \frac{f_H E_{sH}^{\text{inc}}}{f_A E_{sA}^{\text{inc}}} = \frac{[E_s(s)]_H}{[E_s(s)]_A},$$

where the subscript A refers to an animal and the subscript H to a human body. When exposed to electric fields at the same frequency, the current densities will be the same when the electric fields are the same. This means that no scaling is required: the same axial fields induce the same axial current densities and axial electric fields in the body of the man and the body of the animal. This is true when the ratio $[h/a_1]_H = [h/a_1]_A$ and σ_1 is the same in both.

Since *in vivo* experiments with living animals do not seem to have been made with a clear understanding that the large axial electric field in the body is also important in studying cellular effects in internal organs of the body and that scaling for its effects is different from scaling for the corresponding effects of the transverse magnetic field, it is at present difficult to establish useful exposure situations for the formulation of safety guidelines for cellular effects.

3.2.3. In Vitro Studies at the Cellular Level

Extensive research at the cellular level is carried out by exposing tissues and cells in a suitable vessel to magnetic and electric fields. The cells are, of course, not in exactly the same biological environment as when surrounded by a living body, but this is reasonably well approximated. The electromagnetic environment in the sense of exposure to a known macroscopic average field can be very similar. Summaries and discussions of significant results are contained in reviews by Nair, Morgan, and Florig [11], Wood [12], Gandhi [13], and Liburdy [7]. These indicate that an applied electric field or an induced electric field generated by an applied magnetic field can influence a number of cell-membrane-associated processes. Examples are: (a) The enhancement of breast-cancer-cell proliferation by blocking melatonium's action on cell growth by exposure to a 60-Hz magnetic field in the range from 2 to 12 mG $= 0.2$ to 1.2 μT. (b) Increased activity of human lymphoma CEM cells when exposed to a 60-Hz electric field in the range from 1 mV/m to 1 V/m. (c) An increase in human lymphocitic-derived HL-60 cell line by exposure to a 60-Hz magnetic field in the range from 5.7 mG to 5.7 G $= 0.57$ μT to 0.57 mT. The induced electric field is in the range from 1.1 μV/m to 1.1 mV/m. The same effect was observed with an applied electric field of 30 μV/m. (d) A 60-Hz magnetic field of 220 G—generating an induced electric field with maximum of 0.1 V/m—increased calcium-45 influx during signal transduction in the lymphocyte by 50 to 200%. A 60-Hz electric field of 0.17 V/m enhanced the steady-state level of calcium influx. (e) A 30–300-Hz electric field of 0.1 mV/m to 0.1 V/m with a current density $J = 0.05$ to 50 mA/cm^2 affected ion movement through the cell membrane.

These and other experimental results appear to present a reasonable basis for the use of

in vitro measurements in the establishment of meaningful exposure situations. The problem is: What is the relationship between the average macroscopic electric field in an organ of the human body that corresponds to the field applied to cells in an exposure vessel? As pointed out in detail by Polk [14], the electric field and current density generated in a particular organ in the human body when this is exposed to an incident magnetic field are very difficult to determine. This is a consequence of the fact that the electric fields and currents induced by a magnetic field circulate in the body with amplitudes and directions that depend on the distance from the central plane through the body perpendicular to the incident magnetic field. As shown by King and Wu [1], this difficulty does not exist for the axial electric field and current density in the human body when its length is parallel to the large component of the incident electric field. Specifically, as shown by King and Sandler [2], the axial electric field and current density in the spleen of a boy standing near a power line where the vertical electric field is $E_z^{\text{inc}} = 530$ V/m are, respectively, $|E_z^{\text{spleen}}| = 0.41$ mV/m and $|J_z^{\text{spleen}}| = 74.2\ \mu\text{A/m}^2$; the axial electric field and current density in the bone marrow in a boy's leg when standing in the same location are $|E_z^{\text{marrow}}| = 0.63$ mV/m and $|J_z^{\text{marrow}}| = 216.5\ \mu\text{A/m}^2$. These electric fields are the time-average axial electric fields in these organs. They should correspond to electric fields applied across cellular material in exposure dishes provided these are made of styrofoam. Since they have the same order of magnitude as those listed above that have been observed to affect cellular processes, they would seem to offer a useful exposure situation in the ELF range of frequencies.

In vitro studies of the effect of exposure to electromagnetic fields in the VLF range of frequencies do not appear to have been carried out in any extensive manner. Exposure situations closely paralleling those at 60 Hz are readily constructed, but adequate data on observed effects are not available.

In vitro studies at frequencies in the range of 0.1 to 10 GHz are extensive and clearly indicate significant cellular effects from exposure to electromagnetic fields. These are described in summary form in Gandhi [13]. Specifically reviewed are effects of exposure of erythrocytes, leukocytes, and brain and neural cells to electromagnetic fields. The results indicate

both frequency and amplitude dependence. The applied incident electric fields ranged from 2 V/m to 2 kV/m.[1] From King [4], the electric field in the brain (Region 2) due to a hand-held cellular-telephone transceiver with current $I = 0.1$ A in its antenna is of the order $67.8 \exp[-\alpha_2(z-d)]$, where $\alpha_2 = 34.5\ \mathrm{m}^{-1}$ for $\epsilon_{2r} = 51$ and $\sigma_2 = 1.35$ S/m. The field in the brain at distances $z - d$ from the inside surface of the skull (Region 1, thickness $d = 1$ cm) has the values [4]:

$z-d$, cm	0	1	4	6	11
$\lvert E_x \rvert$, V/m	67.8	48	17.2	8.6	2.64

The macroscopic average electric field maintained in the brain when the head is exposed to the electromagnetic field of a hand-held radiotelephone antenna is seen to have the same order of magnitude as the fields that produced significant effects on cellular processes in *in vitro* studies. This suggests that a meaningful exposure situation could be identified, but this would require careful coordination of electric fields in the brain due to a hand-held cellular telephone and fields applied *in vitro* at 0.9 GHz. The latter are not available.

3.3. Exposure Situations and Suggested Guidelines

Suggested exposure guidelines will be based on the electric field generated in the organs of the human body when exposed to a known incident electric field parallel to its length. The intensity of this field which poses a potential hazard is postulated to be equal to or greater than that electric field that produces significant cellular effects *in vitro*.

[1] Much of the exposure data in the 0.1- to 10-GHz range is expressed in terms of the power dissipated as heat per unit mass or the specific absorption rates (SAR). This is meaningful for thermal effects, but is not appropriate for electric-field-dependent cellular effects. The SAR is expressed in units of watts per kilogram and is related to the electric field by the formula SAR(W/kg) $= \sigma E^2/d$, where σ is the real effective conductivity of the medium, d is its mass density, and E is the r.m.s. value of the electric field in the medium. For media that are saturated with water, d is close to 1000 kg/m^3 or 1 g/cm^3. The conductivity σ varies with the tissue and frequency, as shown in Table 6.1 in Gandhi [13]. For nerves and the brain at 300 MHz, it has the value $\sigma = 0.65$ S/m. It follows that, for example, 44 V/m is equivalent to SAR $= 0.65 \times (44)^2/1000 = 1.25$ W/kg. Gandhi [13, p. 248] writes: "The data currently available on the relation of SAR to biological effect shows evidence for biological effects at an SAR of about 1 W/kg."

3.3.1. The ELF Range of Frequencies

In vitro exposure of cellular material to electric fields at 60 Hz indicates that significant effects were observed when $E_z \geq 30\ \mu\text{V/m}$. The vertical electric field in the spleen of a boy with rubber-soled shoes standing 10 m from a 100-kV power line where the electric field is $E_z^{\text{inc}} = 530$ V/m is $|E_z^{\text{spleen}}| = 412\ \mu\text{V/m}$. At a distance of 45 m, the incident field is reduced to $E_z^{\text{inc}} \sim 38$ V/m, and the field in the spleen drops to $|E_z^{\text{spleen}}| \sim 30\ \mu\text{V/m}$. This suggests that for this power line, people should live further away than 45 m where $E_z^{\text{inc}} = 38$ V/m. The associated magnetic field for a traveling-wave power line is $B_y^{\text{inc}} = 0.127\ \mu\text{T}$. These conclusions agree with the epidemiological results for childhood leukemia which indicated distances greater than 50 m for 220–400-kV power lines.

3.3.2. The VLF Range of Frequencies

In the VLF range, there are no exposure situations for which measured *in vitro* effects are available. If the same electric field in the organs of the body as for the ELF range is used, the incident electric field should be less than 20 V/m, the magnetic field less than 0.005 μT = 0.05 mG. People should not live within 1 km of a typical high-power VLF transmitter.

3.3.3. Cellular-Telephone Frequencies

In vitro exposure of brain-cell material in the 0.1–10-GHz range of frequencies shows significant effects when the applied electric field is 44 V/m. A safe value could be set at 4.4 V/m. This means that, for the model of a cellular-telephone antenna at $f = 0.9$ GHz analytically studied [4], most of the brain beyond the skull is exposed to possibly hazardous fields. Since measurements specifically at 0.9 GHz are unavailable and effects may depend on the frequency, more precise conclusions cannot be reached.

4. Discussion of EM Radiation Standards

4.1. Relation to Known Effects

A review of EM radiation standards was carried out, and the effects of EM fields on humans as reported in the extensive literature on the subject were studied. Emphasis was

placed on separating studies on thermal effects from those on non-thermal effects. It was noted that the vast majority of standards and measurements seem to be directed toward the determination of whole-body and localized heating by exposure to EM fields. It is not obvious how thermal standards can be applied in a meaningful manner to non-thermal effects.

An excellent summary of radiofrequency exposure standards can be found in the book by Gandhi [13]. Of particular interest are the ANSI, IEEE and IRPA standards. These standards are mainly concerned with heating effects at high frequencies, although maximum electric and magnetic field strengths are given down to 10 kHz. Some field limits for power-line frequencies are given by Nair *et al.* [11].

Although there are perhaps hundreds of papers on the biological effects of EM fields, two important sources are the book by Polk and Postow [15] and the recent paper by Wood [12]. Work here and overseas indicates that at low frequencies, leukemia has been found in exposed children and adults, and is definitely a concern. At much higher frequencies, many of the biological results are contradictory or inconclusive. In addition, the results of many of the studies are based on laboratory results on cells, and it is difficult to extrapolate the effects to the case of humans.

Standard-setting organizations generally use an SAR (Specific Absorption Rate) of 4 W/kg, averaged over the whole body, as a level at which health effects may take place in humans. This SAR is about 2.5 times the resting energy production rate of the human body. Other researchers, such as Elder and Cahill [16], say that there is evidence that biological effects can occur at an SAR of about 1 W/kg.

4.2. Suggestions for Setting Up Standards

It is important to have some quantitative basis for determining radiation exposure levels with regard to available safety standards and credible research studies. Based on some representative cases, actual fields and currents in the body can be determined. The generic cases under consideration are fields in the body due to: 1) 60-Hz power lines; 2) closely coupled cellular telephones in the 900-MHz region; and 3) the Navy submarine communication system in the 28-kHz region. Actual EM levels found in the body in the various frequency

ranges can be compared to levels that have produced biological effects.

The six components of the electromagnetic field generated by a traveling wave in a three-phase, three-wire, high-voltage power line over a finitely conducting earth have been determined analytically. The currents induced in the body of a man standing under or near such a power line consist of two parts. The first is the axial current induced by the transversely constant part of the vertical component of the electric field and the associated differential part of the transverse magnetic field. The second part is the circulating current induced by the vertically constant part of the horizontal magnetic field and the associated differential part of the vertical electric field. The axial current is determined from the integral equation for an electrically short parasitic antenna; the circulating current is obtained from an integral form of the Maxwell equation $\nabla \times \mathbf{E} = i\omega\mathbf{B}$. The analytically determined currents are shown to be in good agreement with those obtained using the FDTD method. From the total axial current, the current and power densities in different organs in the body can be determined if the shapes, sizes and conductivities of these are known in each cross section. This has been accomplished for a cross section of the human body which includes the spleen and liver.

Possible adverse effects of electromagnetic fields on the human body and especially on the nervous system and the brain are of increasing concern, particularly with reference to cellular telephone transceivers held close to the head. An essential step in the study of this problem is the accurate determination of the complete electromagnetic field penetrating through the skull into the brain. Simple analytical formulas are derived from the theory of the horizontal electric dipole over a layered region. These give the components of the electric and magnetic fields on the air-head surface, in the skin-skull layer, and throughout the brain in terms of a planar model with the dimensions and average electrical properties of the human head. The specific absorption rate (SAR) is also determined.

The VLF antenna in Annapolis, MD, is located on a peninsula between the Severn River and Chesapeake Bay. It consists of a central, base-insulated tower 1200-ft high and an extensive top load of wire panels that are supported by 600-ft towers. Six of these surround

the central tower symmetrically, while three others provide a large extension to the tip of the peninsula. The central tower is driven by a transmitter located several hundred feet from its base. There are three leads from the 300-, 600-, and 900-ft levels of the central tower to the transmitter, where they join in parallel. The antenna is driven against a radial wire ground network buried under most of the area under the top load. Outside of this area, the entire antenna acts like a simple top-loaded, electrically short monopole.

The electromagnetic field maintained by the VLF transmitter at Annapolis induces currents and fields in people living in the urban area within 2 km of the antenna that are greater than those in people living very close to high-voltage power lines. Neither are large enough to have health-related thermal effects, but possibly hazardous non-thermal effects have not been ruled out.

The conclusion of the investigations in this report is that meaningful standards for EM exposure have not been identified. A number of specific exposure situations were investigated in this report where fields were calculated in different parts inside the body, such as the brain or the organs in the stomach. Not available are the experiments that use known exposure fields to find cellular effects *in vitro*. There is also the question of what the correct metric for exposure is. Many researchers use the magnetic field as separate from the electric field values as the metric at low frequencies. However, a more important exposure field is due to the larger longitudinal fields produced in the body by a tangential electric field.

Basic coordination of known field levels in the body and cellular effects has not been carried out. A reasonable approach would require that the physical and biological researchers work together in a unified approach. On the one hand, researchers would calculate internal fields and fields at the cellular level. Based on these fields, hazardous levels could be identified by biologists. Presently, it does not appear that there is much cooperative work taking place. However, interdisciplinary interface, where communication is possible between, for example, electrical engineers and cell biologists, can lead to meaningful EM standards.

5. Conclusions and Recommendations

The investigations carried out under the present program have led to the following conclusions (see also the discussion on setting up standards in Section 3.2 of this report).

1. Meaningful standards for EM exposure are not presently available.

2. EM radiation exposures cannot be done in general, since they require specific physical and EM information.

3. Biological effects of EM radiation cannot be used for setting up standards if the *local* fields inside the body or in cells are not known. A method for determining these fields from external fields is given in [2], which is included in Appendix B. Presently, only *external* fields are used for purposes of standard setting.

4. Simple analytical expressions for fields in the organs of the body are required, which include the dependence on relevant parameters and the direction and magnitude of external fields. Although computational methods are valid, they are complicated and do not give a wide insight into the phenomena. Furthermore, without a knowledge of the field dependence on physical parameters, such as size and frequency, proper scaling is not possible.

Recommendations based on the work in this report are given below:

1. Some meaningful biological effects of EM radiation have been identified in this report, such as leukemia in children near high-power lines, and brain-cell effects in the 0.1–10 GHz range. As experiments become more refined, additional effects will become known. A review of additional effects should be made in a 3–5-year time period.

2. Since EM biological effects can be long-term, some effort should be made to continuously record local EM fields (magnitude and direction) near exposed personnel.

3. One area of investigation that is important appeared in the investigation process. It concerns (a) the calculation of local EM fields across cell membranes and along nerves

and (b) their effect on cell growth and on nerve transmission. This area of research should be explored.

4. The communication band extending from 70–144 MHz was not included in the present study. Here the body length can be of the order of a wavelength, skin effect is significant, and resonance is possible (see the discussion in Section 2.4 of this report). An effort should be undertaken to relate the fields, total current, and current densities inside the body to the external field for this frequency range.

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Appendix A. Evaluation of Government-Furnished Field Measurements

A.1. Introduction

A report entitled "The electromagnetic character of a shielded room" was prepared by NIST [A1] and provided to the principal investigator. Measurements were taken in a shielded room of size 7.87 m $\times$ 8.04 m $\times$ 2.61 m, with no humans in the space. Transmitting antennas were placed at one corner and receiving antennas at the opposite corner. A mechanical timer (i.e., a rotating paddle) was placed between the transmitter and receiver. The electric field was monitored by 10 isotropic probes, having three orthogonal 5-cm dipoles and a single 8-mm dipole. Dipoles were placed on a one meter grid. The system gave two different types of information: a) Swept frequency scans with the tuner spinning and no input power connection; and b) stepped frequency scans using a stepped tuner and input power connections.

A good mode distribution resulted in the 20–1000 MHz range. At the lower frequency range, there were insufficient mode densities to characterize the field. Swept frequency results were only good for establishing likely resonant frequencies. Here the transmitted power variations were not taken into account. From the data, net input power to the chamber could be found along with the VSWR and the field strength. Since the antennas were designed to work in free space, their characterization in the chamber is different than their normal operating conditions. A normalization factor S was defined as

$$S = \left[\frac{\text{Reference Power}}{\text{Input Power}}\right]^{1/2} = \left[\frac{1}{\text{Input Power}}\right]^{1/2},$$

where the reference power is taken as 1 W. The E fields were multiplied by S to correct them with respect to the input power. Along with the mode-stirred maximum results for the electric field, RSS values were given, where E_{RSS} is given by

$$E_{RSS} = \sqrt{E_x^2 + E_y^2 + E_z^2}$$

Special sources were provided by the sponsor for characterization in the chamber.

A.2. General Comments

No general conclusions about electromagnetic effects can be drawn from the measurements. Specific antennas and antenna systems were characterized by finding electric-field values as a function of frequency. Care must be taken in interpreting these results with respect to characterization in their actual environment. The actual environment includes having humans exposed to the field. Knowing the ambient field does not give information on the field inside the body, and the currents in various organs. Such information for certain frequency ranges is found in the main body of this report. Since standards are available along with levels causing effects, some comments can be made about field levels in the chamber. However, as discussed elsewhere in this report, standards are questionable, since they have not been related to fields inside the body or fields found to cause effects on the cellular level. It should also be noted that standards are based on heating or thermal effects. When these thermal values are translated to field values, they may have no significance with respect to *actual* field values that can cause hazardous biological effects.

A.3. Comparison with Standards for Human Exposure to Radio Frequency Electromagnetic Fields

A set of summary tables for radio frequency protection standards is given below. Note that the plane-wave equivalent power-density values are not appropriate for near-field conditions.

A.3.1. IEEE Standards (IEEE C95.1–1991, Revision of ANSI C95.1–1982)

In Tables 5 and 6 [A2], the exposure values in terms of electric and magnetic field strengths are the values obtained by spatially averaging values over an area equivalent to the vertical cross section of the human body (projected area). These plane-wave equivalent power-density values, although not appropriate for near-field conditions, are commonly used as a convenient comparison with MPE's at higher frequency and are displayed on some instruments in use.

Table 5. Maximum Permissible Exposure (MPE) for Controlled Environments

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (E Field, H Field) (mW/cm^2)	Averaging Time E^2, H^2 or S (minutes)
0.0003–0.1	614	163	(100, 1000000)	6
0.1–3.	614	$16.3/f$	$(100, 10000/f^2)$	6
3–30	$1842/f$	$16.3/f$	$(900/f^2, 10000/f^2)$	6
30–100	61.4	$16.3/f$	$(1, 10000/f^2)$	6
100–300	61.4	0.163	1	6
300–3000			$f/300$	6
3000–15000			10	6
15000–300000			10	$616000/f^{1.2}$

Table 6. Maximum Permissible Exposure (MPE) for Uncontrolled Environments

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (E Field, H Field) (mW/cm^2)	Averaging Time (minutes) E^2, S	Averaging Time (minutes) H^2
0.0003–0.1	614	163	(100, 1000000)	6	6
0.1–1.34	614	$16.3/f$	$(100, 10000/f^2)$	6	6
1.34–3	$823.8/f$	$16.3/f$	$(180/f^2, 10000/f^2)$	$f^2/0.3$	6
3–30	$823.8/f$	$16.3/f$	$(180/f^2, 10000/f^2)$	30	6
30–100	27.5	$158.3/f^{1.668}$	$(0.2, 940000/f^{3.336})$	30	$0.0636 f^{1.337}$
100–300	27.5	0.0729	0.2	30	30
300–3000			$f/1500$	30	
3000–15000			$f/1500$	$90000/f$	
15000–300000			10	$616000/f^{1.2}$	

A.3.2. ANSI (1982) [A3] American National Standards Institute (ANSI C95.1)

The data in [A3] on radio frequency protection guides are presented in Table 7.

The results in the government supplied report which are for named antennas (discones, bicones, log-periodic, stove pipes and special sources) are given in Figures 22–36 of the report. Note that these results have been corrected for input power. The maximum electric field found in these figures is about 10 V/m, and the majority of the maximum field values are around 1 V/m. As far as the IEEE and ANSI standard levels for Maximum Permissible Exposure (MPE), the systems in Figures 22–36 are all below the MPE levels. Some results are within an order of magnitude of the MPE, and are in the 30–144 MHz range. For example, for special source #2, Figure 34 (whip transmitter, bicone receiver) and special source #3, Figure 36, the electric-field peaks occur approximately at 27.36 MHz and 142 MHz, respectively.

A.4. References

[A1] Koepke, G., Melquist, D., and Camell, D., "The electromagnetic character of a shielded room—a search for maximum field strength," Natl. Inst. of Stand. and Tech., Report SR-813-20-94, Boulder, CO, 1994.

[A2] *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*, IEEE, NY, 1992.

[A3] *American National Standard Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 300 kHz to 100 GHz*, IEEE, NY, 1982.

Table 7. Radio Frequency Protection Guides, f in MHz

Frequency Range (MHz)	E^2 (V^2/m^2)	E (V/m)	H^2 (A^2/m^2)	Power Density (mW/cm^2)
0.3–3	400000	547	2.5	100
3–30	4000 $(900/f^2)$	63.2 $(30/f)$	0.025 $(900/f^2)$	$900/f^2$
30–300	4000	63.2	0.025	1
300–1500	4000 $(f/300)$	63.2 $(\sqrt{f/300})$	0.025 $(f/300)$	$f/300$
1500–100000	20000	141.2	0.125	5

Appendix B. Published Papers Related to This Contract

1. King, R. W. P., and Wu, T. T., "The complete electromagnetic field of a three-phase transmission line over the earth and its interaction with the human body," *J. Appl. Phys.*, **78**, 668–683, 1995.

2. King, R. W. P., and Sandler, S. S., "Electric fields and currents induced in organs of human body when exposed to ELF and VLF electromagnetic fields," *Radio Sci.* **31**, 1153–1167, 1996.

3. King, R. W. P., and Harrison, Jr., C. W., "Electromagnetic field in human body due to VLF transmitter," pp. 121–123 in *Proceedings of the 1995 IEEE 21st Annual Northeast Bioengineering Conference*, S. Wolpert, D. H. Brooks, and J. R. LaCourse, Eds., IEEE Service Center, Piscataway, NJ, 1995.

4. King, R. W. P., "The electromagnetic field generated in model of human head by simplified telephone transceiver," *Radio Sci.* **30**, 267–281, 1995.

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